Development and performance of a linear induction motor based on the effect of flux-concentration by eddy currents

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Development and performance of a linear induction motor based on the effect of flux-concentration by eddy currents

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Abstract. This paper has reported the development and performance of a flux-concentration type linear induction motor (FCLIM) utilizing the effect of flux-concentration by eddy currents. In the developed FCLIM, the slot-leakage flux is reduced and as a result more flux is concentrated into the air gap. The key element of the FCLIM is the conducting plate inserted between the exciting coils in each slot. Thrust characteristics of conventional tubular LIM and FCLIM are compared using the equivalent circuit parameters. Though some losses are occurred in the plate, the overall efficiency of FCLIM is better at higher output force.

1. Introduction

In the case of normal (i.e., conventional type) tubular linear induction motor (LIM), due to the higher value of leakage reactance, the air gap flux is decreased. On the other hand in the case of flux-concentration type linear induction motor (FCLIM), due to the flux-concentration effect, the leakage flux is reduced and more flux is concentrated into the air gap, resulting in an increase of the developed thrust. A flux-concentration type linear induction motor of fixed stator type has been developed in our laboratory and has already been reported [1]. Recently another model of FCLIM, the stator of which can move over the secondary rail, has been developed. This paper has reported the development and performance of our present model of FCLIM based on the principle of the flux-concentration by eddy currents [2]. The key element of the FCLIM is the conducting plate inserted between the exciting coils in each slot. The eddy currents induced in the conducting plate create a counter mmf, which opposes the passage of the slot leakage flux. This paper also presents the secondary-core flux density distributions of the FCLIM. The secondary-core flux density distribution along the motor length has been measured and it has been found that the secondary-core flux density distribution along the motor length is better for the FCLIM than that of the normal type tubular LIM. The performance of the FCLIM and normal tubular LIM are determined using the equivalent circuit parameters [3]. It has been observed from the calculated results using the equivalent circuit parameters and the experimental results that the FCLIM has better

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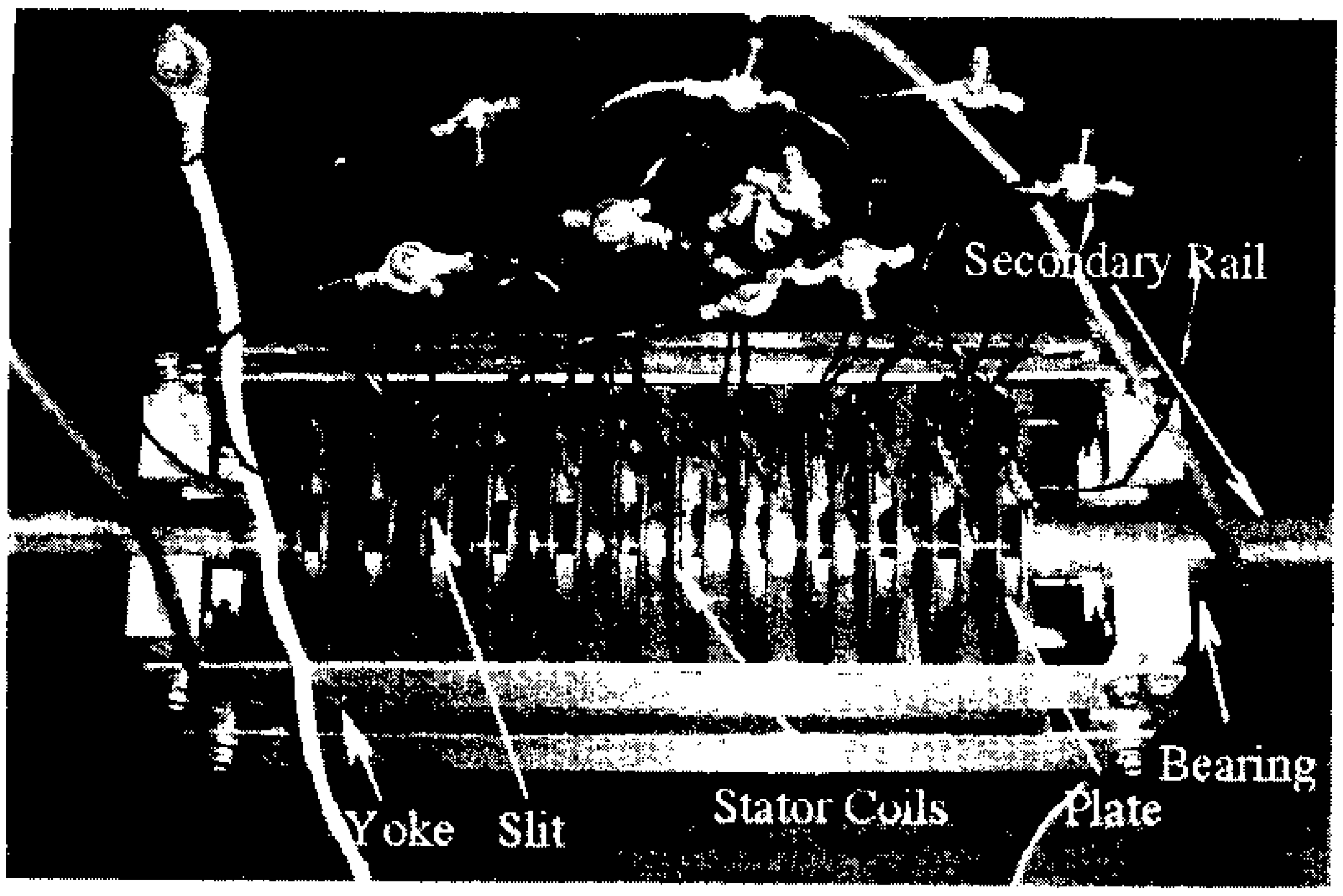

Fig. 1. Fabricated set up of 4-pole FCLIM.

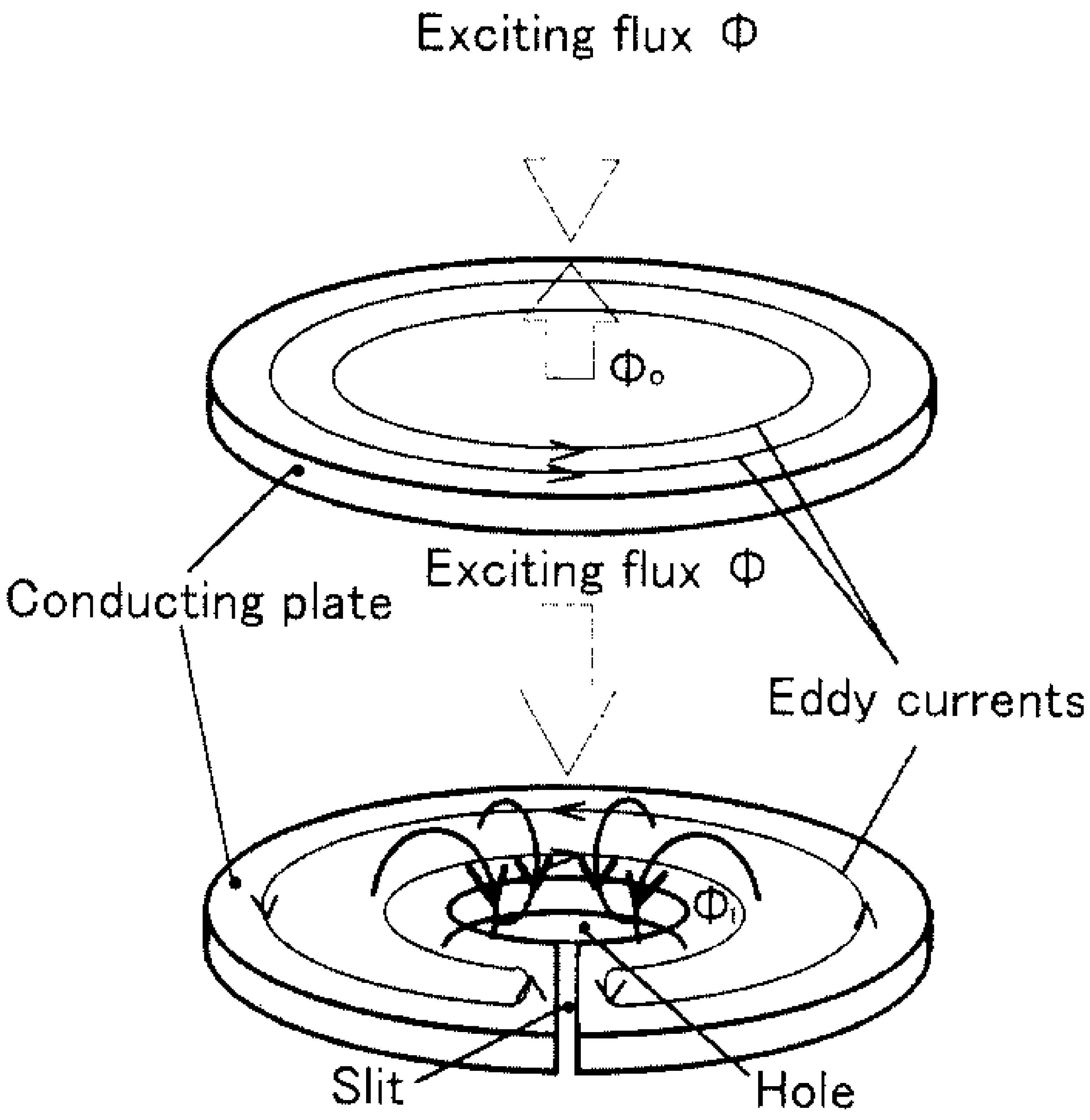

Fig. 2. Effect of the conducting plate with a radial slit.

thrust-characteristics compared to that of conventional type tubular LIM and the overall efficiency of FCLIM is better at higher output force. The present model of FCLIM is suitable for the applications like transport of loads, factory automation etc. It can also be used for the applications where short linear motion is required, for example for opening or closing valves.

2. Constructional features of FCLIM

Figure 1 shows the fabricated set-up of a 4-pole FCLIM, which has an annular-linear configuration. When a three-phase source is applied, a traveling electromagnetic field is produced in the air gap.

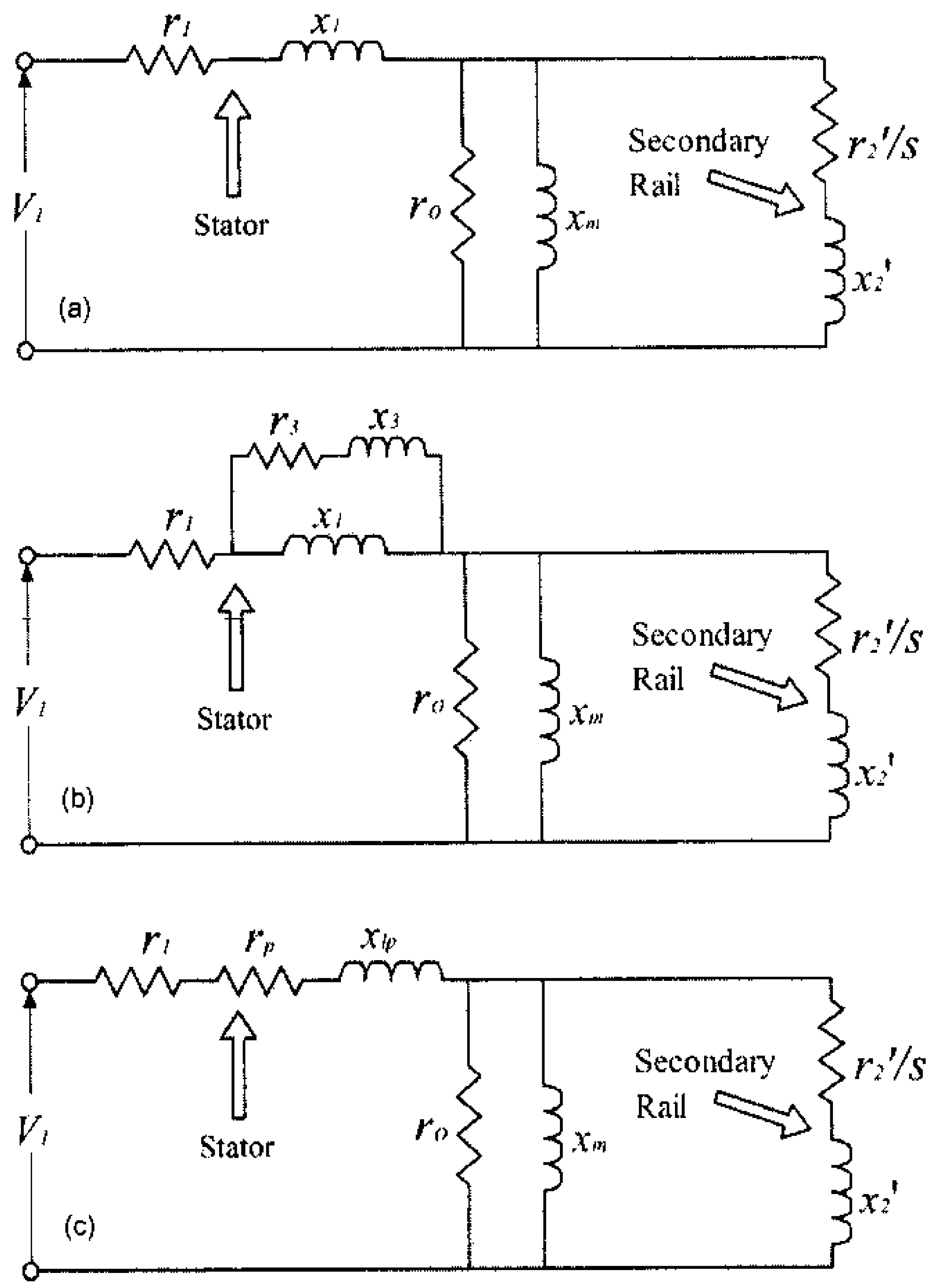

Fig. 3. Equivalent circuit a) of conventional LIM b) considering the effect of the plate c) of LIM.

The conducting plate, along with the exciting coils of 38 turns, is inserted in each of the 12 slots. The conducting plate has an air hole in its center and a slit in the radial direction. When an external alternating field is applied, eddy currents are induced in the conducting plate. The slit forces the eddy currents to flow around the air hole. The cross-section of the conducting plate is T-shaped. Figure 2 shows the effect of the conducting plate along with the slit. The plate has high reluctance; therefore, the majority of the magnetic flux is flowing through the yoke, air gap and secondary core. Thus the plate with radial slit provides some sort of magnetic shield, which results in reduction of the leakage flux between the yokes and the concentration of flux into the air gap.

Five yokes made of laminated silicon steel are arranged radially. The length and outer diameter of the stator are 224 mm and 126 mm respectively. The pole pitch is 54 mm. The width of the slit is 15.4 mm. The secondary rail is made of solid cylindrical iron core and a copper sleeve surrounding it. The outer diameter of the copper tube is 30 mm. The construction is very rugged and the transverse edge effect does not exist due to cylindrical construction. Also there is no normal force due to cylindrical symmetry.

3. Determination of equivalent circuit parameters

Figure 3a shows the per phase equivalent circuit of conventional type tubular LIM. Here x_m, r_0, r_1 and r'_2 are the magnetizing reactance, core loss resistance, primary (i.e., stator) resistance and secondary resistance referred to primary respectively. x_1 is the primary leakage reactance due to the primary leakage flux, which links only the primary winding. Primary leakage reactance mainly includes the slot

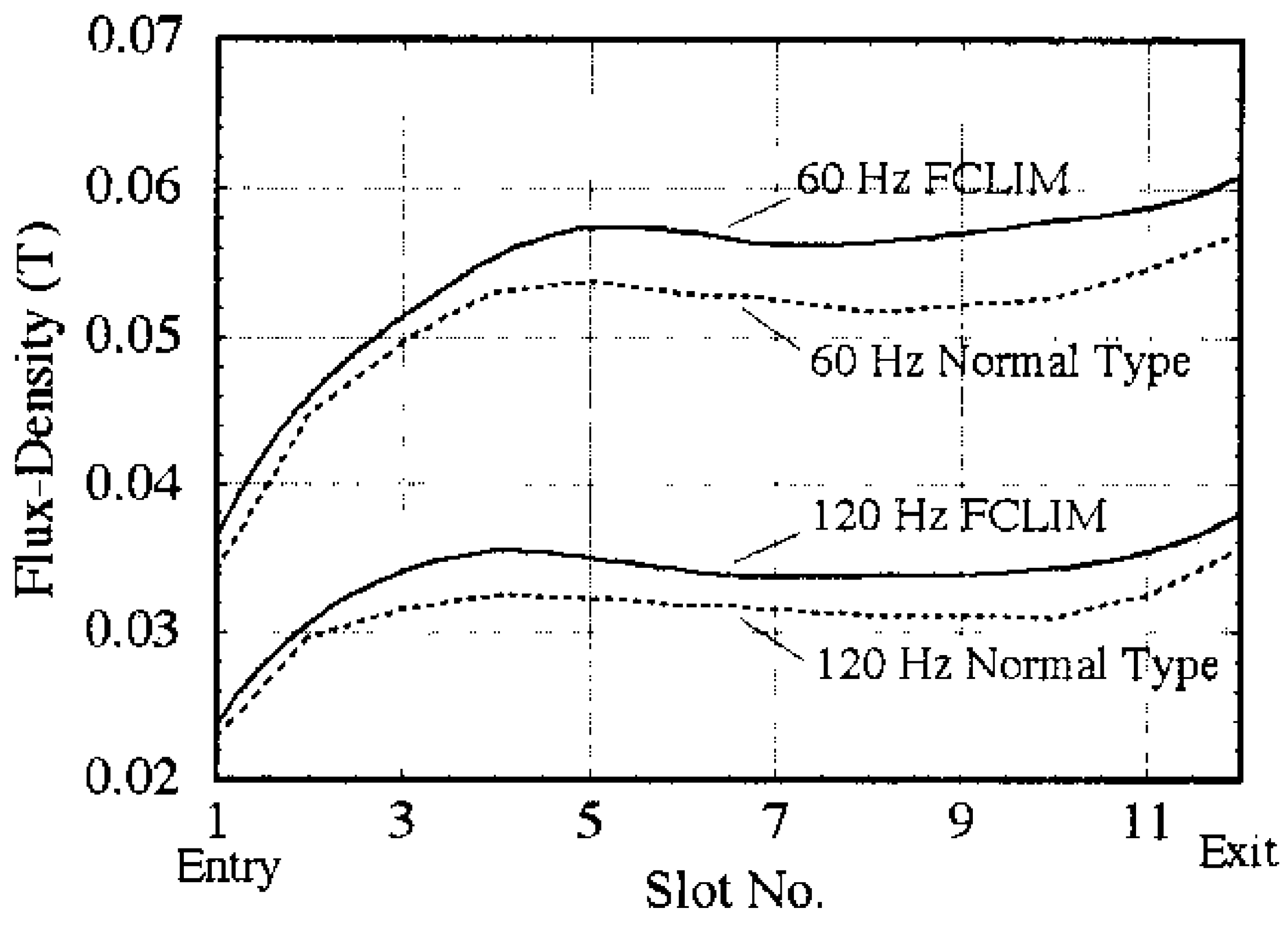

Fig. 4. Secondary-core flux density distribution.

leakage reactance and the overhang leakage reactance. x'_2 is the secondary leakage reactance referred to primary due to the secondary leakage flux, which links only the secondary. The plate, inserted between the stator coils, links the stator leakage flux. Hence in the presence of plate, a resistance in series with a leakage reactance (i.e., r_3 and x_3) will act in parallel with the stator leakage reactance i.e., x_1 as shown in Fig. 3b. Figure 3c shows the resultant per phase equivalent circuit of FCLIM. Here r_p is the resistance due to the effect of the plate and x_{lp} is the stator leakage reactance in the presence of plate.

The following experimental steps are adopted for the determination of equivalent circuit parameters of FCLIM and conventional type tubular LIM.

i) Measurement of stator resistance.

ii) Measurement of the voltage across the search coil wound around the iron core in the absence of the copper tube to determine the magnetizing reactance. The magnetizing reactance is determined under both conditions i.e., without plate and with plate.

iii) No load test without plate to determine the core loss resistance. The stator leakage reactance in the absence of the plate is determined using the test results of the no load test without plate and the values of the magnetizing resistance and the core loss resistance.

iv) Blocked-rotor test without plate to determine the secondary resistance. Since the copper of the secondary is not placed in the slots, the secondary leakage reactance is neglected.

v) No load test with plate to determine the resistance due to the effect of the plate and the stator leakage reactance in the presence of plate (using the values of r_1, x_m and r_0).

In the presence of the plate between the stator coils in each slot, the value of the stator leakage reactance is decreased by a factor K given by [4].

$$K = \frac{(\sinh 2\alpha d - \sin 2\alpha d) + 2(\sin\alpha d \cosh\alpha d - \sinh\alpha d \cos\alpha d)}{\alpha d(\cosh 2\alpha d - \cos 2\alpha d)} \tag{1}$$

where αd is the effective depth of the plate. αd is given by

$$\alpha d = 1.06 d\sqrt{\frac{rf}{60}} \tag{2}$$

where d, in cm, is the depth of the plate placed under the stator conductors, r is the ratio of the effective plate width to the slot width and f is the supply frequency.

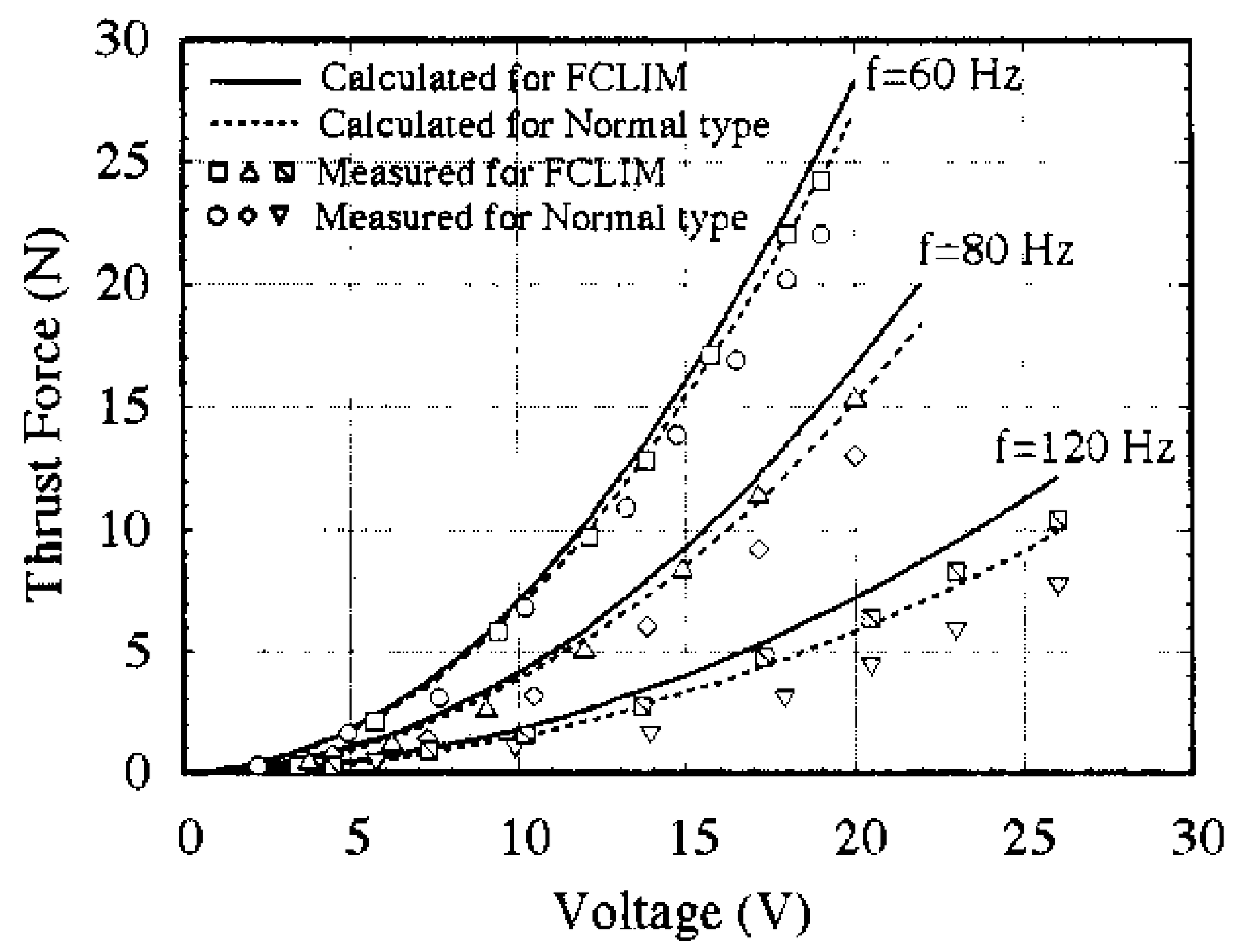

Fig. 5. Standstill thrust vs. voltage characteristics.

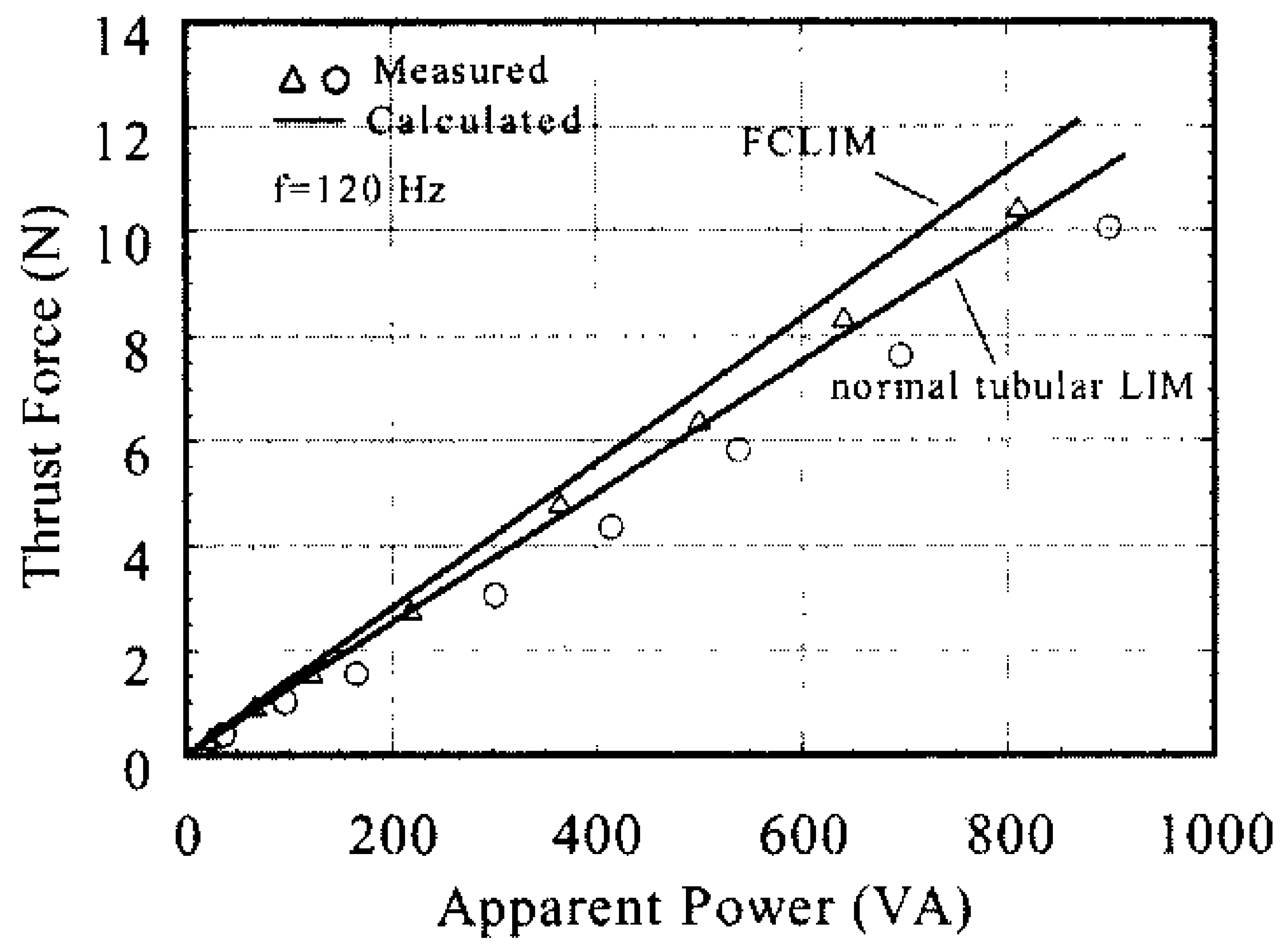

Fig. 6. Thrust force vs. apparent power characteristics.

The thrust force calculations are done using Eq. (3).

$$F = 3\frac{I_2'^2 r_2'}{2\tau f s} \tag{3}$$

where F is the developed thrust force, τ is the pole pitch, s is the slip and I_2' is the secondary current per phase referred to stator.

4. Experimental results

The secondary-core magnetic flux density distribution under standstill condition has been measured by search coils wound around the secondary rail under each slot. Figure 4 shows the secondary-core flux density distributions along the motor length under standstill condition at 60 and 120 Hz respectively. The values of the secondary-core flux densities are smaller due to the higher value of the cross-sectional area of the secondary-core. At the entry end the magnetic field is weakened by the entry end effect, the field is built up gradually and there are sharp rises on the distribution curves near the exit end. All the

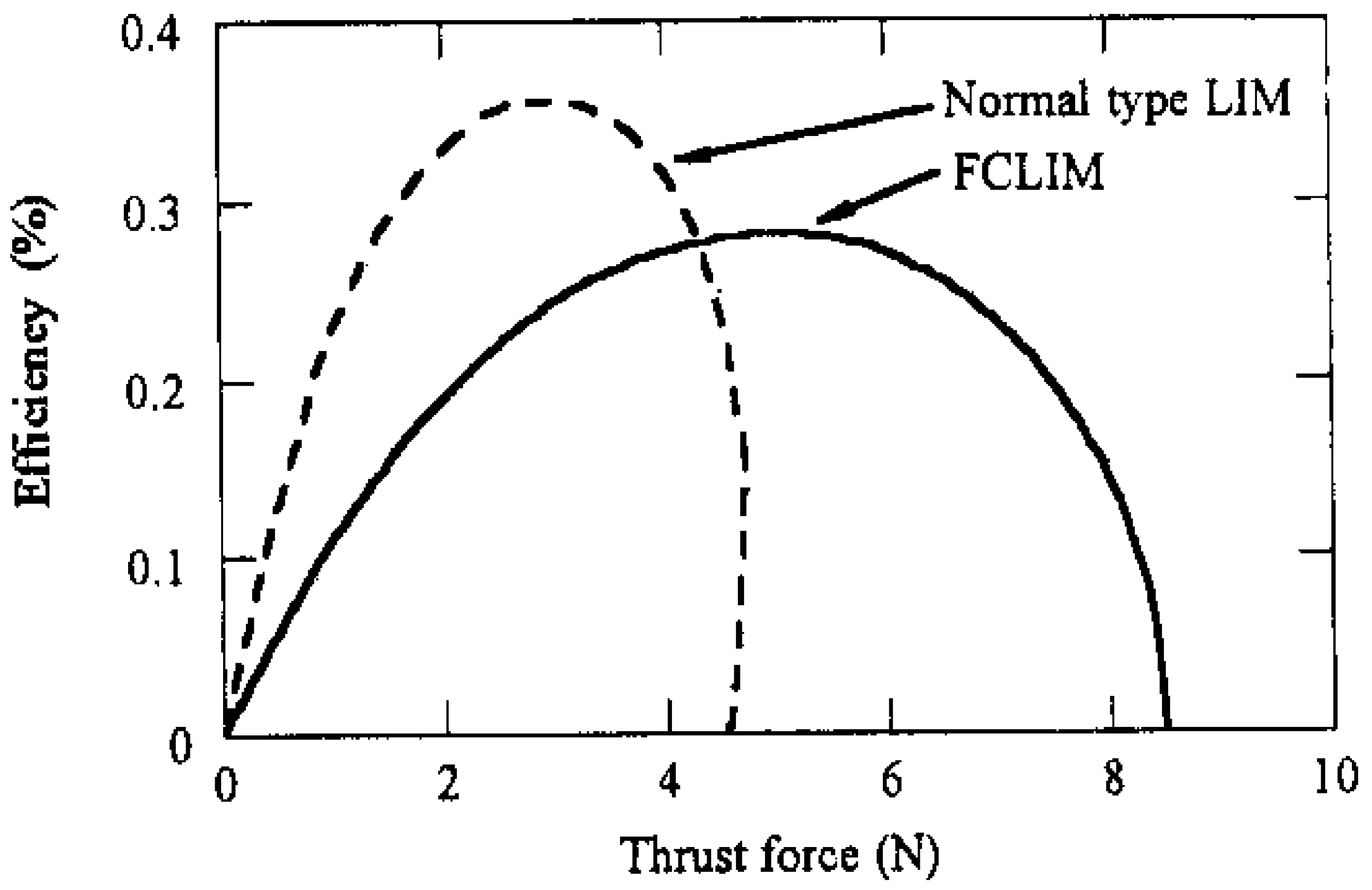

Fig. 7. Efficiency vs. thrust force characteristics.

curves have been measured with the same stator current of 5 A. The values of flux densities for FCLIM are higher than those for normal type tubular LIM. Figure 5 shows the standstill thrust vs. voltage characteristics of the FCLIM and those of the conventional type tubular LIM at 60, 80 and 120 Hz respectively. The effect of the plate is pronounced at higher frequencies. The frequency is adjusted by using a pulse width modulated (PWM) inverter and the input voltage is adjusted by using a three-phase voltage regulator. Thrust force has been measured by using a load cell. Figure 6 shows the thrust vs. apparent power characteristics of FCLIM and normal type tubular LIM at a stator supply frequency of 120 Hz. It is observed that for a constant input VA the thrust developed is more in case of FCLIM than that of normal type tubular LIM. Figure 7 shows the efficiency vs. thrust force characteristics of FCLIM and conventional type tubular LIM. It is evident from Fig. 7 that the efficiency of FCLIM is better at higher thrust force.

5. Conclusions

This paper has reported the development and performance of a novel flux-concentration type LIM. Due to the flux-concentration effect by eddy currents, the secondary-core flux density distribution along the motor length is better for the FCLIM than that of the normal type tubular LIM. In FCLIM the leakage flux is reduced considerably and the air gap flux is increased. The close agreement between experimental and calculated results has confirmed the validity of the developed equivalent circuit of FCLIM. It is confirmed from the calculated and experimental results that the performance of the FCLIM is superior than that of normal type tubular LIM. The developed FCLIM is suitable for short-stroke and lower speed applications.

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